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INTERVENTION ANALYSIS OF WATER QUALITY RECORDS[1]

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ABSTRACT: The impoundment of the Kootenai River by Libby Dam caused changes in discharge and water quality in the river downstream from Lake Koocanusa. The changes observed downstream were largely attributable to the depth of withdrawal from the reservoir and the reservoir's ability to store and mix various influent water masses. The preimpoundment and postimpoundment time series of discharge and six water quality variables were autocorrelated and exhibited strong seasonality. Intervention analysis, a technique employing Box-Jenkins time series models, was used to quantify the nature and magnitude of the changes in water quality after the construction of Libby Dam. The models were developed with data from June 1967 through February 1981 and were able to satisfactorily forecast riverine conditions from March 1981 through January 1982.
(KEY TERMS: intervention analysis; water quality; time series modeling; stochastic modeling.)

INTRODUCTION

A frequent goal in the analysis of time series data is to determine if an event in the period of record produced significant changes in the mean values of variables in the data set. Classical statistical tests, such as the Student's t-test, can test for differences in mean values; however, most of these statistical tests make the assumption that the errors are normally and independently distributed. These assumptions often are violated by sequential data (Box and Tiao, 1975). Time series modeling is an appropriate method for analyzing sequential data that are highly autocorrelated and exhibit strong seasonal effects. Intervention analysis is a stochastic time series modeling technique suggested by Box and Tiao (1975) and Hipel, *et al.* (1975), for rigorously analyzing whether or not a natural or man induced intervention causes a significant change in the mean level of a time series. Intervention analysis has been successfully applied to sequential streamflow data (Hipel, *et al.*, 1975, 1977a, 1977b; Lettenmaier and Burges, 1981; Baracos, *et al.*, 1981. Time series analysis has recently been suggested by Whitfield and Schreier (1981) and Whitfield (1983) to be suitable for detecting changes in water quality over time. McLeod, *et al.* (1983), present an analysis of water quality series using intervention analysis.

This paper discusses the use of intervention analysis for statistically describing and modeling streamflow and water quality variables, and the effects of impoundment on these variables. The intervention models were developed with data collected from June 1967 through February 1981 at the two stations on the Kootenai River immediately downstream from Libby Dam. Data collected from March 1981 through January 1982 were used to independently validate the intervention models.

In March 1972 the Kootenai (spelled Kootenay in Canada) River was impounded by Libby Dam in northwestern Montana to form Lake Koocanusa (Figure 1), a large reservoir operated to provide flood storage, hydroelectric power, and recreation benefits. Water quality data have been collected since 1967 by the U.S. Geological Survey approximately 6 km downstream of the present location of Libby Dam; streamflow has been measured since 1961. These data were collected to monitor the effects on the Kootenai River caused by construction and operation of Libby Dam.

DATA USED

The variables sampled included the following: instantaneous streamflow, monthly mean streamflow, water temperature, specific conductance, silicate, nitrate plus nitrite, orthophosphorus, and pH. Annual reports of the U.S. Geological Survey tabulate the data and describe or refer to the methods used to collect and analyze the data. Values for each variable were reduced to one per month by averaging within those months where more than one observation was available. Monthly mean discharges were calculated from the series of daily mean discharges. Instantaneous discharges were taken at the time of water quality samplings.

Libby Dam was built as part of a treaty between the United States and Canada for cooperative development of the water resources of the Columbia River basin. Construction began in the spring of 1966; Lake Koocanusa was officially im-

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pounded on March 21, 1972. The 148-km-long reservoir receives drainage from 23,271 km^2, or 47 percent of the Kootenai River basin (Figure 1). Characteristics of the basin have been discussed in detail by Bonde and Bush (1975), Water Resources Services (1976), and Woods and Falter (1982).

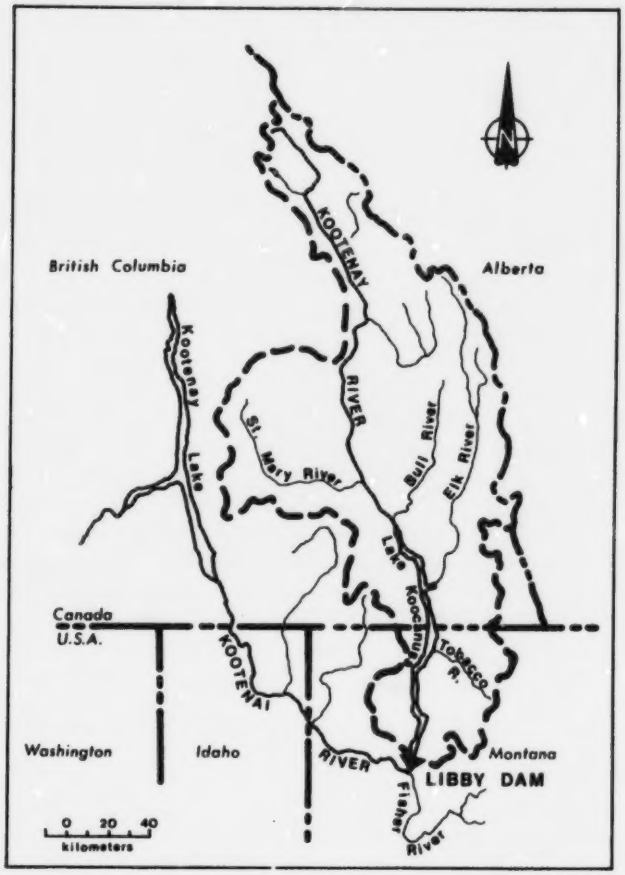

Figure 1. Kootenai River Basin and Location of Libby Dam and Lake Koocanusa.

Lake Koocanusa has a wide range of reservoir volumes and surface areas. At a maximum pool altitude of 749.50 m, the reservoir contains 7.16 km^3 and has a surface area of 188 km^2. Minimum operational pool is at an altitude of 697.08 m and yields a volume of 1.08 km^3 and a surface area of 59.10 km^2. A cyclic pattern of May-June inflow and winter drawdown produces large fluctuations in reservoir volume each year. Lake Koocanusa generally has a maximum yearly volume during July through September and a minimum during March and April.

The Kootenai River ceased to be free flowing on August 2, 1971 (Storm, *et al.*, 1980a), although it was not until late March of 1972 that the first water passed through the permanent sluiceways of Libby Dam. These sluiceways are one of the three types of outlet structures on the concrete gravity dam. The three sluiceways have invert altitudes of 671.17 m and can release 1,784 m^3s^{-1} with the reservoir pool at its maximum altitude. Two spillway bays have invert altitudes of 733.00 m and, at maximum pool altitude, can release 4,049 m^3s^{-1}.

Four operational penstocks (eight ultimately) have invert altitudes of 677.30 m. The combined maximum hydraulic capacity of the four turbines served by the penstocks is 651.30 m^3s^{-1} at a gross head of 87.80 m. The four turbines came on-line on the following dates: August 10 and October 10 of 1975 and January 21 and March 31 of 1976. The penstocks have a selective withdrawal system consisting of a series of vertical piers and horizontal bulkheads. This system permits admitting water to the penstocks from altitudes ranging from the penstock inverts to within about 6 m of the reservoir surface at its maximum altitude. The selective withdrawal system became operational in June 1977. Reservoir releases can be passed through any combination of the outlet structures.

Effects of Impoundment

Instantaneous and monthly mean discharges were clearly affected by impoundment (Figures 2 and 3). Prior to impoundment, about 70 percent of the river's annual mean discharge occurred in the spring and early summer as a result of snowmelt runoff (Bonde and Bush, 1975). Following impoundment, the majority of spring snowmelt runoff was temporarily stored in Lake Koocanusa for flood control and hydroelectric power production. As a result, discharges during May through July were reduced by impoundment. Discharges during September through March were increased after impoundment because the volume of Lake Koocanusa had to be reduced to provide adequate storage for next year's snowmelt runoff. Impoundment failed to clearly affect August discharges. The changes in discharge attributable to flood control operations overshadowed those caused by operation for hydroelectric power production because patterns of discharge did not change substantially after the autumn of 1975, when hydroelectric power production commenced.

The range of discharge was also affected by impoundment. From 1967 through 1971 daily mean discharges ranged from 37 to 2,078 m^3s^{-1} (Bonde and Bush, 1975), whereas from 1972 through 1980 they ranged from 54 to 1,059 m^3s^{-1}. This damping of discharge extremes is a characteristic of many regulated streams.

Water temperatures were substantially altered by impoundment (Figure 4). Postimpoundment temperatures were higher than preimpoundment temperatures in October through February, no significant change occurred in March, and temperatures were lower in April through September. These temperature shifts occurred because impounded Kootenai River water gained and lost heat quite differently than it had as a free flowing river. Large and deep reservoirs such as Lake Koocanusa are capable of storing large quantities of heat; however, the large volume warms more slowly during the summer than does a free flowing river. During periods of atmospheric cooling this stored heat is then lost more slowly by a reservoir

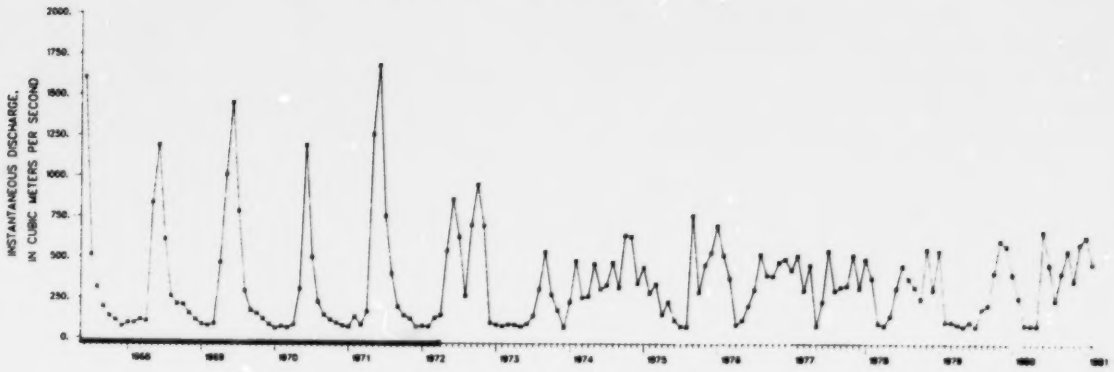

Figure 2. Monthly Instantaneous Discharges for the Kootenai River Downstream from Libby Dam Site. The preintervention period is indicated by the heavy base line.

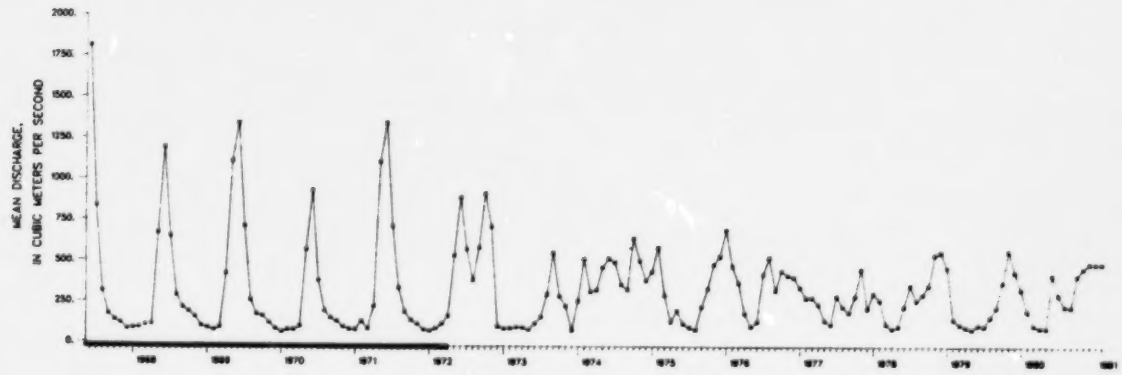

Figure 3. Monthly Mean Discharges for the Kootenai River Downstream from Libby Dam Site. The preintervention period is indicated by the heavy base line.

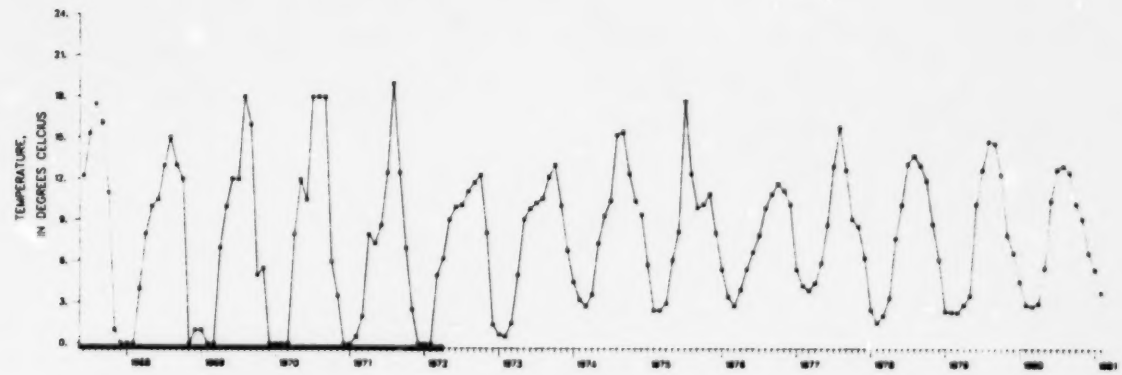

Figure 4. Monthly Temperatures of the Kootenai River Downstream from Libby Dam Site. The preintervention period is indicated by the heavy base line.

than a river. Time depth diagrams of water temperatures in Lake Koocanusa near the dam (Woods and Falter, 1982) reveal that only during August did the upper 10 m of the reservoir possess temperatures similar to summer temperatures in the river prior to impoundment. These diagrams also show that water temperatures between 7° and 9°C prevailed throughout the water column during December near the dam; the free flowing river in December typically was near 0°C.

The amount of temperature change was also a function of the dam outlet through which water was released from Lake Koocanusa. A chronological record of these releases is listed in Storm, *et al.* (1980a). The sluiceways were used almost exclusively from initial impoundment until August 24, 1975, at which time penstock releases commenced. Sluiceways and penstocks were used simultaneously until March 6, 1976, after which time penstocks intercepted water deep within the reservoir; hence, the temperature of released water did not exceed 12°C during the summer of 1976. Spillway releases that exceeded one week in duration occurred from August 8 to November 4, 1974, and from July 1 to August 20, 1975. Warmer, near surface water was released by the spillways in August and September of 1974 and in July of 1975 (Figure 4). However, this warming effect is not evident in October of 1974 because reservoir cooling and consequent circulation had commenced. Beginning in July 1977 the selective withdrawal system was used to supply water to the penstocks. Operating the system involves sequential placement of bulkheads as the reservoir pool is raised and then, as the pool is lowered, the bulkheads are sequentially removed. The following periods include the data on which the first bulkhead was installed and the last one removed: June 1 to October 12, 1977; April 19, 1978, to January 1, 1979; May 29, 1979, to February 26, 1980; and May 12 to December 15, 1980. The effect of the selective withdrawal system on water temperature is evident for June through September because the water released in 1977 through 1980 was, in general, warmer than water released in those months in prior years (Figure 4). The effects of the selective withdrawal system on water temperature is not as evident during other months, probably because reservoir cooling and circulation lessened temperature differences through the water column.

Impoundment of the Kootenai River decreased specific conductance in July through April, increased it in May and June and altered the seasonal pattern of specific conductance (Figure 5). The changes in specific conductance in 9 of the 12 months were inversely related to discharge changes. Although this inverse relation is often observed it did not fully account for the observed changes in specific conductance, because the reservoir's storage capacity permitted mixing of a variety of discharges with their associated specific conductances. The specific conductance during May and June in preimpoundment years was largely determined by the volume of snowmelt runoff carried by the Kootenai River; however, after impoundment this snowmelt runoff was intercepted and mixed with other water stored in Lake Koocanusa. Therefore, specific conductance downstream from Libby Dam was largely controlled by the depth of water release at the dam and the distribution of specific conductance in Lake Koocanusa.

The extensive lacustrine habitat created by impoundments such as Lake Koocanusa typically is colonized rapidly by phytoplankton. Phytoplankton growth clearly lowered concentrations of silicate (Figure 6), nitrate plus nitrite (Figure 7) and orthophosphate (Figure 8), all of which are essential nutrients for phytoplankton. The sharp decline in these nutrient concentrations suggests that biological uptake was more rapid than release of these three nutrients from inundated soils and vegetation within the reservoir. Prior to impoundment, concentrations of these nutrients were, in general, lowest in the summer, reflecting their utilization by riverine algae. This pattern was not consistently repeated in the river downstream from the dam after impoundment. The concentrations of silicate, nitrate plus nitrite, and orthophosphate measured in the Kootenai River downstream of the dam were, as with specific conductivity, largely a function of the depth-of-water withdrawal and the reservoir's ability to mix and store water masses with varying constituent concentrations.

Silicate concentrations after impoundment were lower than preimpoundment values in all months but June (Figure 6). The increase in June likely occurred because released water had intercepted silicate that had been resuspended by the spring freshet. The winter drawdown dewaters a large part of the

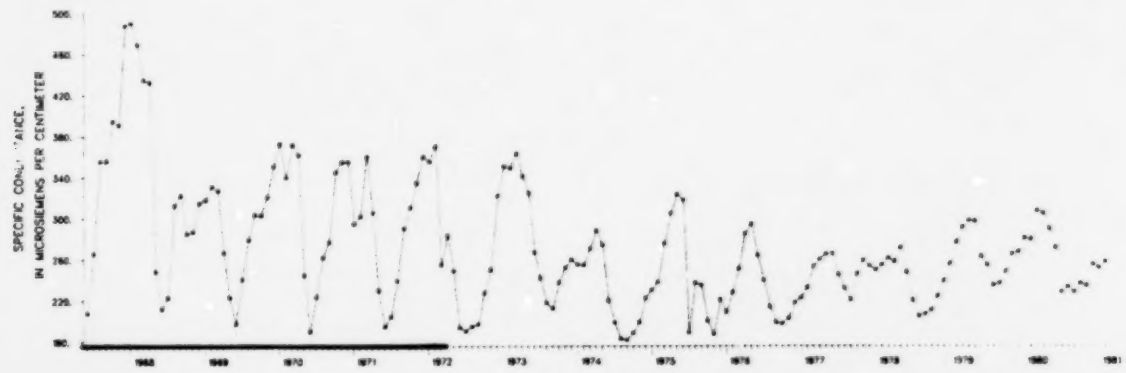

Figure 5. Monthly Specific Conductances of the Kootenai River Downstream from Libby Dam Site. (The preintervention period is indicated by the heavy base line.

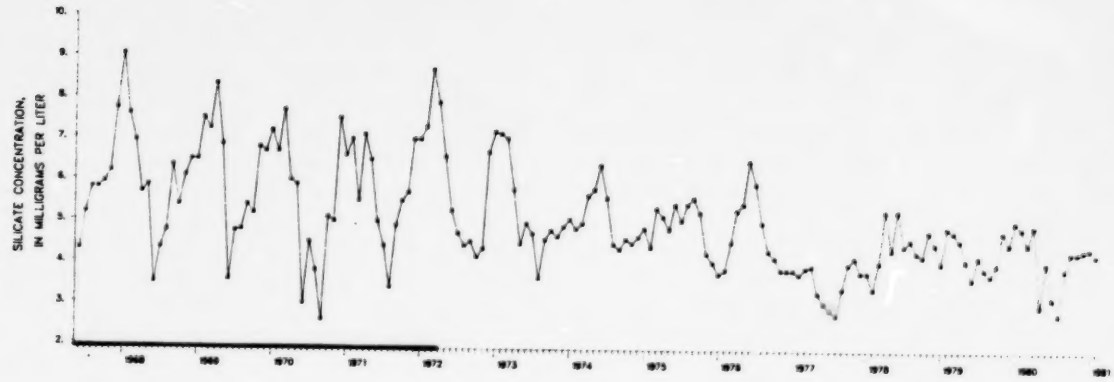

Figure 6. Monthly Silicate Concentrations from the Kootenai River Downstream of Libby Dam Site. The preintervention period is indicated by the heavy base line.

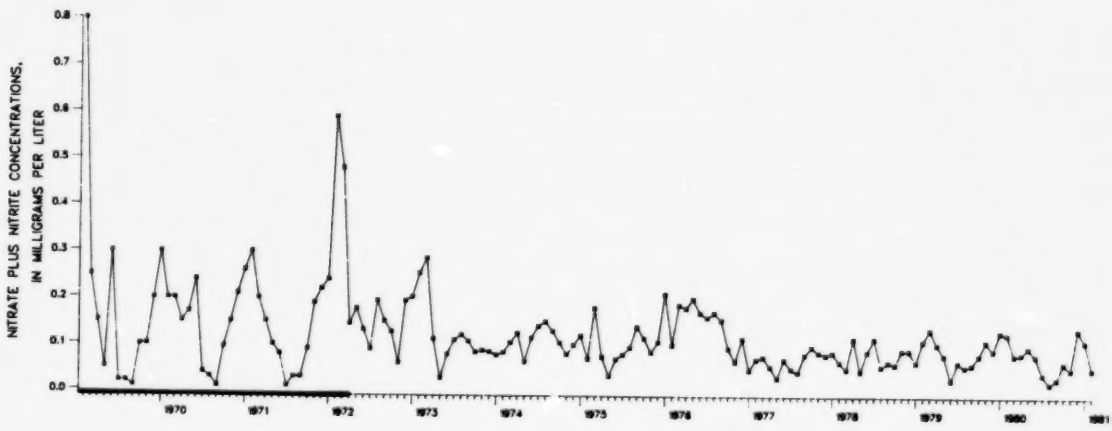

Figure 7. Monthly Nitrate Plus Nitrite Concentrations from the Kootenai River Downstream of Libby Dam Site. The preintervention period is indicated by the heavy base line.

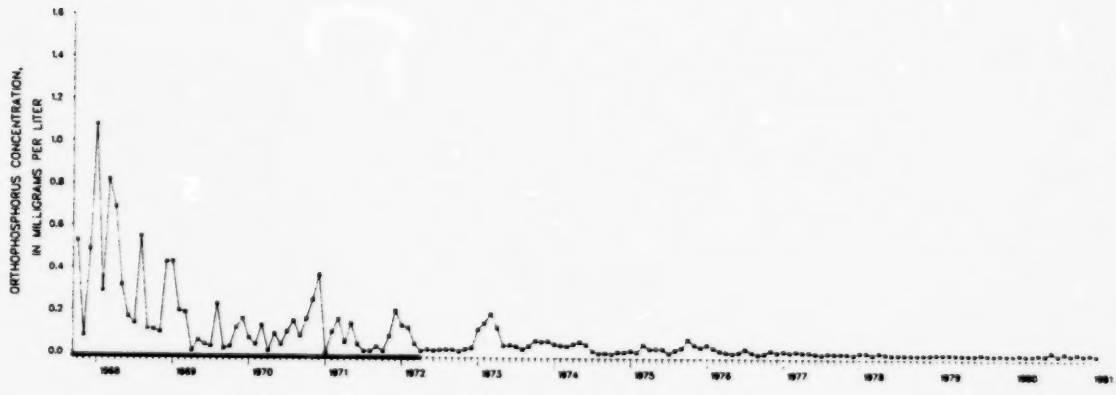

Figure 8. Monthly Orthophosphorus Concentrations from the Kootenai River Downstream of Libby Dam Site. The preintervention period is indicated by the heavy base line.

reservoir's bottom and side slopes which are then susceptible to erosion during the spring freshet. Typically, the spring freshet is colder than the upper layer of Lake Koocanusa and, therefore, inflow initially proceeds along the reservoir bottom as underflow before becoming interflow (Woods and Falter, 1982). These inflow events have the potential to deliver large quantities of suspended and dissolved constituents to the release structures at Libby Dam.

Postimpoundment concentrations of nitrate plus nitrite were generally smaller than preimpoundment concentrations in November through June, generally larger in July through September (Figure 7), and generally unchanged in October. The postimpoundment increases in summertime nitrate plus nitrite might be caused, in part, by nitrification of organic nitrogen as it settled downward from the euphotic zone. Lake bottom sediments that were resuspended by the spring freshet might have also provided a source of nitrogenous material available for nitrification. Dissolved oxygen profiles for the reservoir (Storm, *et al.*, 1980b) verify that the oxygenated conditions necessary for nitrification were available at and above the depth of the water release structures.

Postimpoundment concentrations of orthophosphorus were generally lower than preimpoundment values in all months (Figure 8). Although part of this reduction can be attributed to utilization by phytoplankton, much of the reduction was due to sedimentation of phosphorus in Lake Koocanusa. Studies by Iskander and Shukla (1981) of phosphorus chemistry in Lake Koocanusa sediments revealed that the reservoir was functioning as a phosphorus sink; the sediments also had little tendency to desorb phosphorus. Woods (1982) reported than an average of 63 percent of the annual loading of total phosphorus delivered to Lake Koocanusa was retained by the reservoir; substantial declines consequently occurred in the loadings of total phosphorus downstream of Libby Dam. Although total phosphorus is not directly addressed in this report, total phosphorus behaved similarly to orthophosphorus in Lake Koocanusa.

The pH of the free flowing Kootenai River ranged from 7.1 to 8.3 and lacked a definite seasonal trend. Water discharged from Lake Koocanusa tended to have a higher pH, especially after 1973 (Figure 9). Months with noticeable increases in pH after impoundment were December through February and May through August; no months had decreases in pH. Data on the vertical distribution of pH in Lake Koocanusa (Storm, *et al.*, 1980b) showed that pH generally was highest near the surface and lowest near the bottom, except during periods of reservoir circulation, when pH was nearly uniform throughout the water column. Such conditions would be expected in light of the photosynthetic utilization of carbon dioxide in the euphotic zone and the respiratory release of carbon dioxide beneath the euphotic zone. These biologically induced effects on pH were blended by reservoir hydrodynamics. The seasonal patterns in pH after the impoundment (Figure 9) are the result of this mixing and the change in depth of water release.

INTERVENTION MODELS

It is obvious, then, that the construction and operation of Libby Dam had an affect on the chemistry of the Kootenai River. The changes can be described in the general manner stated above. What we are principally interested in is whether or not these changes can be quantified.

In general, an intervention model consists of two components, one dynamic and one stochastic. The dynamic component uses transfer function parameter estimates to describe the intervention effects (Hipel, *et al.*, 1977b) whereas the stochastic component, in the form of an autoregressive integrated moving average (ARIMA) model about the process describes the natural variation in the modeled variable. Box and Tiao (1975) describe the building of an intervention model making use of the autocorrelated nature of the data series to quantify the effects of an induced change on that series. Their intervention analysis uses a special type of Box-Jenkins transfer function noise model to describe the changes in the mean level of a time series caused by induced effects.

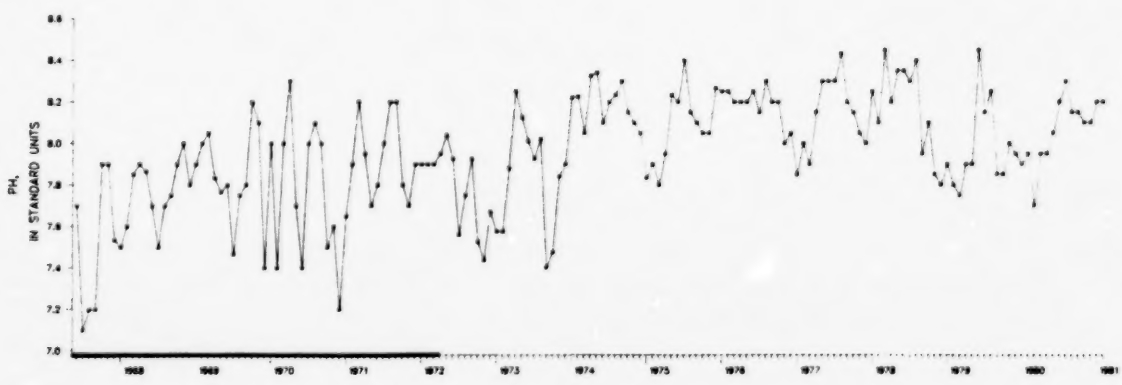

Figure 9. Monthly pH Values from the Kootenai River Downstream of Libby Dam Site. The preintervention period is indicated by the heavy base line.

As indicated by Tiao, *et al.* (1975), the process of model building is iterative. The successive use of identification, fitting and diagnostic checking is used in establishing the model. We have followed their strategy of (1) framing a model for change which describes what is expected to occur, given knowledge of the actions which have been known to be taken; (2) working out the appropriate data analysis based on that model; (3) if diagnostic checks show no inadequacy in the model form, conclusions as to the effects of the change may be drawn directly from the analysis; but (4) if the model appears inadequate, then trying to learn how and why, and then revising the model. They followed this approach to study the effect of pollution controls on smog intensity over the city of Los Angeles.

In the system of interest the major intervention which took place was the construction and operation of Libby Dam. Hipel, *et al.* (1977a), suggest the model to estimate for the monthly effect of reservoir operation is

$$y_t \quad y = x_t + \sum_{i=1}^{12} \omega_{0i} (\xi_{ti} \quad \xi_i) + \frac{a_t}{1 - \phi_1 B} \qquad (1)$$

where y_t is the series of equally space observations of a variable, x_t is a deterministic series of monthly preintervention means, and ω_{0i} the transfer function parameter for the ith month (i.e., ξ_{ti}=1 in month i after the intervention and 0 in month i prior to intervention). In general we entertained models of a similar form.

Identification Techniques

Hipel, *et al.* (1977a), describe the two basic steps to identify the intervention part of the dynamic component as:

(1) Ascertain the types of changes in the time series.

(2) Choose appropriate transfer functions and intervention series to model the intervention changes. The intervention series consist of 0's and 1's and can be a pulse or step. If the intervention affects different seasons in a particular manner, a dynamic model can be designed for each season or group of months that are changed in the same fashion.

Hipel, *et al.* (1977a), indicate that various techniques are available for use in Step 1 above. For seasonal data a plot of the series before and after the intervention and some other methods described subsequently are useful for postulating models.

Box and Jenkins (1976) suggested the identification of an ARIMA model using the autocorrelation function (ACF) and the partial autocorrelation function (PACF), and to identify the degree of differencing required. The ACF and PACF of our data sets were significantly different from zero at lags of 1 and 12. This indicates that, in a plot of a series, low values will be grouped together and high values will follow other high values, and these groups will recur at an interval of 12 months. The models used were estimated using the method of conditional least squares (Liu, 1979). Since these estimates have standard errors calculated, it is possible to determine the statistical significance of the estimated parameters. If the input response series has been transformed, a necessary transformation may be calculated.

DISCUSSION OF RESULTS

Using the techniques described by Hipel, *et al.* (1977b), for identifying potential models we selected likely models for each of the variables. These models are identified in Table 1. The transformation applied to the variables and the results of the Portmanteau goodness of fit test (Ljung and Box, 1976) are also given in this table. All values of the goodness of fit test were less than the critical value of 48.6 (for 36 lags). Deviations greater than this critical value would be expected in 90 percent of the cases, suggesting that these models are adequate.

The cumulative sum identification technique (Hipel, *et al.*, 1977a) suggested that each month was affected in a different manner, by the intervention, for all variables. Therefore each of the models include intervention parameters for the specific months of the year. These monthly terms have the benefit of providing estimates that allow one to evaluate the alterations of the seasonal patterns.

Table 2 contains the parameter estimates for the various models with their standard errors. These results suggest that these eight variables were significantly affected by the operation of Libby Dam. Each variable was affected in a unique manner. These parameters are based on the natural logarithmic transformed data, with the exception of pH and temperature. For the variables which were transformed, the parameter estimates were transformed to percent change as described by Hipel, *et al.* (1977a), i.e.:

$$\% \text{ change} = 100 (e^{\omega 0 j} \quad 1) \qquad (2)$$

Table 3 contains the estimated changes for each month of the year in units appropriate to each variable. The instantaneous and monthly mean discharges show large increases in discharges during the winter months and substantial decreases during May and June. Temperature changes derived from parameter estimates show the decrease in spring and summer temperatures and the increase in winter temperatures. These estimates also show that instead of a simple decrease of the summer highs and an increase in winter lows, as evident in Figure 4, there is a substantial shift in the temperature pattern.

Parameter estimates for specific conductance show a substantial increase during May and June, a period during which discharges are sharply reduced by the operation of the reservoir. A substantial decrease in the conductance is present during the rest of the year, this decrease being greatest during the winter months concurrent with substantial increases in discharge.

Silicate concentrations decreased in all months except June, which shows a 42 percent increase in concentration. Prior to the intervention, June silicate concentrations were the lowest

TABLE 1. Intervention Models for the Eight Variables, the Data Transformation Used and the Test of Goodness of Fit. The critical value for the goodness of fit test at 90 percent is 48.6 for 36 lags.

	Variable	Transformation	Portmanteau Lack of Fit
$y_t-\bar{y} = \sum_{i=1}^{12} \omega_{oi}(\xi_{ti}-\xi_i) + \frac{(1-\phi_1 B)(1-\theta_2 B^{12})}{1-B^{12}} a_t$	Monthly Mean Discharge	ln	29.5
	Instantaneous Discharge	ln	24.7
	Specific Conductance	ln	29.8
	Silicate	ln	33.3
	pH	–	34.4
	Nitrate + Nitrite	ln	29.1
$y_t-\bar{y} = \sum_{i=1}^{12} \omega_{oi}(\xi_{ti}-\xi_i) + \frac{(1-\theta_1 B)(1-\theta_2 B^{12})}{1-B^{12}} a_t$	Temperature	–	44.9
$y_t-\bar{y} = \sum_{i=1}^{12} \omega_{oi}\frac{(\xi_t)}{1-B^{12}} + \frac{(1-\phi_1 B)(1-\theta_2 B^{12})}{1-B^{12}} a_t$	Orthophosphate	ln	26.3

observed during the year; with the exception of April and July all decreases in silicate concentrations were significant (Table 2). These decreases were generally about 25 percent.

Changes in pH were significant (Table 2) in only three months (May, June, and December). Changes ranged from 0.25 in December to 0.41 pH units in May.

Changes in Nitrate plus nitrite (Table 3) show large increases in concentration in July through September and decreases from November through March. Changes in April, May, and October are not significantly different from zero.

Perhaps the most interesting results are the changes in orthophosphate concentrations. For orthophosphate the units of change are percent per year. All model parameter estimates are significantly different from zero and the monthly changes of the variable range from a minimum of 31 percent per year in November to a maximum of 60 percent per year in March. What these changes indicate is that orthophosphorus concentrations decreased during the years following the impoundment of the Kootenai River, suggesting that Lake Koocanusa is an effective trap for orthophosphorus.

The results of the intervention models are in agreement with the observed changes in water quality variables. The intervention model parameters and their appropriate transformations give rigorous estimates of the nature and magnitude of the changes in water quality variables which resulted from the construction and operation of Libby Dam. Intervention analysis provides a method to perform critical evaluations of the effects of interventions such as Libby Dam.

Model Validation

Model validation was performed by comparing actual and forecast values. Data collected from March 1981 to January 1982 was not included in the series to be modeled. The models developed were used to forecast future values for the period from February 1980 to March 1982.

The first 13 values forecast are compared with actual values used in developing the model. The last 11 forecast values were compared with actual values which had not been used in formulating the model. Table 4 summarizes the results of the validation tests. Generally, the forecast results were within one standard error of the actual measurements. Only five forecasts were greater than two standard errors from the actual measurements. These were distributed between observations included in model formation and those observations which were independent of the model. Forecast values greater than one standard error were also distributed between the two sets of actual measurements. Generally, all eight models provided satisfactory forecasts of the future observations. These results provide an assurance as to the adequacy of the models in describing the effects of the intervention of Libby Dam on the water quality of the Kootenai River.

CONCLUSIONS

The creation of the Libby impoundment altered the water quality of the Kootenai River downstream of the damsite. The alterations have been attributed to limnological processes which took place within the reservoir that was created. The application of time series methods, in particular intervention models, allowed the monthly changes in water chemistry to be quantified, and tested for significance. The results of intervention analysis were consistent with the observed limnological processes. Intervention analysis is a valuable tool in analyzing the types of changes observed.

TABLE 2. Intervention Model Parameter Estimates with Standard Errors Indicated in Parenthesis. The values indicated with an asterisk (*) are not significantly different from zero.

Variable	ϕ_1	θ_2	January ω_{01}	February ω_{02}	March ω_{03}	April ω_{04}	May ω_{05}	June ω_{06}	July ω_{07}	August ω_{08}	September ω_{09}	October ω_{010}	November ω_{011}	December ω_{012}
Monthly Mean Discharge	0.6606	0.8424	1.2622	1.0988	0.6743	0.0225*	−1.4217	−1.5872	−0.7954	0.0019*	0.7288	1.1862	1.3830	1.0187
	(0.0648)	(0.0700)	(0.3337)	(0.3238)	(0.3016)	(0.3141)	(0.3271)	(0.3332)	(0.3379)	(0.3401)	(0.3413)	(0.3410)	(0.3399)	(0.3379)
Instantaneous Discharge	0.4501	1.2183	1.0268	0.9884	0.2039	0.7860	−1.6355	−1.4096	−0.0524*	−0.0937*	0.8289	1.3509	1.5509	1.5047
	(0.0733)	(0.758)	(0.2049)	(0.1506)	(0.1758)	(0.2433)	(0.1430)	(0.1535)	(0.2242)	(0.1444)	(0.1460)	(0.1707)	(0.1498)	(0.1439)
Specific Conductance	0.7894	0.6840	−0.2215	−0.1933	−0.0241*	0.0668*	0.3493	0.3162	0.0377*	−0.2044	−0.3170	−0.3355	−0.3234	−0.2865
	(0.0563)	(0.0752)	(0.1150)	(0.1058)	(0.0944)	(0.0969)	(0.1082)	(0.1163)	(0.1215)	(0.1260)	(0.1233)	(0.1223)	(0.1202)	(0.1187)
Silicate	0.6346	1.8204	−0.6601	−0.4342	−0.3153	−0.0389*	−0.2234	0.3496	−0.0091*	−0.2843	−0.2556	−0.2686	−0.3221	−0.5045
	(0.0649)	(0.0838)	(0.1203)	(0.0962)	(0.0897)	(0.1066)	(0.0992)	(0.0984)	(0.0941)	(0.1156)	(0.1078)	(0.0958)	(0.0946)	(0.0958)
pH	0.5382	0.5906	0.0483*	0.0459*	−0.1203*	0.1220*	0.4117	0.3637	0.1235*	0.0450*	−0.0447*	−0.0866*	−0.0385*	0.2519
	(0.0731)	(0.0839)	(0.2202)	(0.2157)	(0.1966)	(0.1964)	(0.2151)	(0.2189)	(0.2336)	(0.2358)	(0.2349)	(0.2215)	(0.2221)	(0.2214)
Nitrate + Nitrite	0.4044	0.7771	−0.8709	−0.9330	−0.3810	−0.3279*	−0.0637*	−0.8276	1.5959	1.5575	2.1689	0.0137*	−0.4959	−0.5821
	(0.0826)	(0.1071)	(0.3597)	(0.3810)	(0.3772)	(0.3492)	(0.3915)	(0.3848)	(0.3591)	(0.3671)	(0.3812)	(0.3585)	(0.3704)	(0.3583)
	ϕ_1	θ_2	ω_{01}	ω_{02}	ω_{03}	ω_{04}	ω_{05}	ω_{06}	ω_{07}	ω_{08}	ω_{09}	ω_{010}	ω_{011}	ω_{012}
Temperature	−0.2262	0.9193	3.9546	2.6174	−0.7162*	−3.8379	−2.9468	−2.3563	−3.0359	−4.7196	−3.1942	1.7129	8.0124	6.6612
	(0.0823)	(0.0732)	(1.0088)	(1.0086)	(1.0725)	1.0032	(1.0093)	(1.1052)	(1.0485)	(1.0101)	(1.0469)	(1.2802)	(1.1013)	(1.0094)
	ϕ_1	θ_2	ω_{11}	ω_{12}	ω_{13}	ω_{14}	ω_{15}	ω_{16}	ω_{17}	ω_{18}	ω_{19}	ω_{110}	ω_{111}	ω_{112}
Orthophosphate	0.3701	0.8688	−0.5196	−0.5338	−0.9138	−0.6016	−0.5213	−0.5447	−0.5409	−0.6086	−0.4768	−0.5976	−0.3663	−0.7753
	(0.0792)	(0.0600)	(0.1764)	(0.1545)	(0.1742)	(0.1605)	(0.1568)	(0.1541)	(0.1609)	(0.1706)	(0.1617)	(0.1578)	(0.1528)	(0.1563)

TABLE 3. Estimated Changes in Each Month for the Variables from Intervention Model Parameter Estimates.

Variable	Units of Change	January	February	March	April	May	June	July	August	September	October	November	December
Monthly Mean Discharge	Percent	253.32	200.06	96.27	2.27	−75.87	−79.55	−54.86	0.19	107.26	227.46	298.68	176.96
Instantaneous Discharge	Percent	179.21	168.69	22.62	119.46	−80.51	−75.57	−5.11	−8.94	129.08	286.09	371.57	350.28
Specific Conductance	Percent	−19.8	−17.6	−2.4	6.9	41.8	37.2	3.8	−18.5	−27.1	−28.5	−27.6	−24.9
Silicate	Percent	−48.3	−35.2	−27.0	−3.8	−20.0	41.8	−1.0	−24.7	−22.6	−23.6	−27.5	−39.6
pH	pH Units	0.048	0.046	−0.120	0.122	0.412	0.364	0.124	0.045	−0.045	−0.087	−0.039	0.252
Nitrate + Nitrite	Percent	−58.14	−60.66	−31.68	−27.96	−6.17	−56.29	393.27	374.69	774.86	1.38	−39.09	−44.13
Temperature	^{o}C	3.95	2.62	−0.72	−3.84	−2.95	−2.36	−3.04	−4.72	−3.19	1.71	8.01	6.66
Orthophosphorus	%/Year	−40.5	−41.4	−59.9	−45.2	−40.6	−42.0	−41.8	−45.5	−37.9	−44.9	−30.6	−53.9

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LITERATURE CITED

Baracos, P. C., K. W. Hipel, and A. I. McLeod, 1981. Modeling Hydrologic Time Series from the Arctic. Water Resources Bulletin 17(3): 414-422.

Bonde, T. J. H. and R. M. Bush, 1975. Kootenai River Water Quality Investigations, Libby Dam Preimpoundment Study 1967-1972. U.S. Army Corps of Engineers, Seattle District, 124 pp.

Box, G. E. P. and G. M. Jenkins, 1976. Time Series Analysis: Forecasting and Control. Holden-Day, San Francisco, California, 575 pp.

Box, G. E. P. and G. C. Tiao, 1975. Intervention Analysis with Applications to Economic and Environmental Problems. Journal of American Statistical Association 70:70-79.

Hipel, K. W., W. C. Lennox, T. E. Unny, and A. I. McLeod, 1975. Intervention Analysis in Water Resources. Water Resources Research 11:855-861.

Hipel, K. W., A. I. McLeod, and E. A. McBean, 1977a. Stochastic Modeling of the Effects of Reservoir Operation. Journal of Hydrology 32:97-113.

Hipel, K. W., A. I. McLeod, and W. C. Lennox, 1977b. Advances in Box-Jenkins Modeling I. Model Construction. Water Resources Research 13:567-575.

Iskander, I. K. and S. S. Shukla, 1981. Limnological Investigations: Lake Koocanusa, Montana, Part 5: Phosphorus Chemistry of Sediments, Hanover, New Hampshire. U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory Special Report 81-15, 9 pp.

Lettenmaier, D. P. and S. J. Burges, 1981. Validation of Synthetic Streamflow Models. *In*: Proceedings of the International Conference on Time Series Methods in Hydrosciences. Burlington, Ontario.

Liu, D. M., 1979. User's Manual for BMDQ2T Time Series Analysis (Box-Jenkins). University of California, Los Angeles, California, 105 pp.

Ljung, G. and G. E. P. Box, 1976. Studies in the Modeling of Discrete Time Series 3: A Modification of the Overall X^2 Test for Lack of Fit in Time Series Models. University of Wisconsin, Department of Statistics, Technical Report No. 477.

McLeod, A. I., K. W. Hipel, and F. Comacho, 1983. Trend Assessment of Water Quality Time Series. Water Resources Bulletin 19:537-547.

Storm, P. C., T. J. H. Bonde, R. M. Bush, and J. W. Helms, 1980a. Libby Dam Postimpoundment Study Basic Data 1972-1978, Vol. 1, Introduction. U.S. Army Corps of Engineers, Seattle District, 115 pp.

Storm, P. C., T. J. H. Bonde, R. M. Bush, and J. W. Helms, 1980b. Libby Dam Postimpoundment Study Basic Data 1972-1978, Vol. 2, Lake Koocanusa Water Quality Profile. U.S. Army Corps of Engineers, Seattle District, 437 pp.

Tiao, G. C., G. E. P. Box, and W. J. Hamming, 1975. Analysis of Los Angeles Photochemical Smog Data: A Statistical Overview. Journal of the Air Pollution Control Assoc. 25:260-268.

Water Resources Services, 1976. Kootenay Air and Water Quality Study, Phase 1, Water Quality in Region 4, the Lower Kootenay River Basin. Victoria, British Columbia, Department of Environment, 190 pp.

Whitfield, P. H., 1983. Evaluation of Water Quality Sampling Locations on the Yukon River. Water Resources Bulletin 19(1):115-121.

Whitfield, P. H. and H. Schreier, 1981. Hysteresis in Relationships Between Discharge and Water Chemistry in the Fraser River Basin, British Columbia. Limnology and Oceanography 26:1179-1182.

Woods, P. F., 1982. Annual Nutrient Loadings, Primary Productivity and Trophic State of Lake Koocanusa, Montana and British Columbia 1972-80. U.S. Geological Survey Professional Paper 1283, 24 pp.

Woods, P. F. and C. M. Falter, 1982. Limnological Investigations: Lake Koocanusa, Montana. Part 4: Factors Controlling Primary Productivity. Hanover, New Hampshire. U.S. Army Corps of Engineers. Cold Regions Research and Engineering Laboratory, 106 pp.

TABLE 4. Intervention Model Validation. Observed (OBS) and forecast (FCST) values with standard errors (SE). Differences greater than one standard error are indicated by * and greater than two standard errors by **.

	ℓ_n-Instantaneous Discharge			ℓ_n-Monthly Mean Discharges			Temperatures			Specific Conductance			pH			ℓ_n-Silicate Concentrations			ℓ_n-Nitrate + Nitrite			ℓ_n-Orthophosphate		
	OBS	FCST	SE	OBS	FCST	SE	OBS	FCST	SE	OBS	FCST	SE	OBS	FCST	SE	OBS	FCST	SE	OBS	FCST	SE	OBS	FCST	SE
February 80	9.13	9.34	0.48	8.82	9.15	0.42	2.9	2.87	2.09	5.63	5.66	0.10	7.95	7.89	0.24	2.18**	1.64	0.16	−2.08	−2.24	0.49	−5.81	−6.74	1.61
March 80	8.08*	8.76	0.52	8.23*	8.80	0.50	2.8	3.56	2.15	5.73	5.70	0.13	7.70	7.96	0.27	1.50	1.64	0.18	−2.52	−2.11	0.53	−6.91	−6.91	1.72
April 80	8.07	8.34	0.53	8.08	8.50	0.53	3.0	3.90	2.15	5.72	5.72	0.15	7.95	8.04	0.28	1.59	1.70	0.19	−2.48	−2.26	0.54	−6.91	−6.89	1.74
May 80	8.05	8.35	0.53	8.05	8.55	0.55	5.6	6.65	2.15	5.67	5.71	0.16	7.95	8.12	0.28	1.09**	1.54	0.20	−2.34	−2.79	0.54	−5.40	−6.68	1.74
June 80	10.06	9.15	0.53	9.59*	8.79	0.55	10.5	10.02	2.15	5.61	5.56	0.16	8.05	8.34	0.28	1.39	1.60	0.20	−2.52	−2.64	0.54	−6.21	−6.91	1.74
July 80	9.70	9.18	0.53	9.27	9.06	0.55	12.8	12.60	2.15	5.43	5.48	0.17	8.20	8.20	0.28	1.16*	1.51	0.20	−3.22*	−2.42	0.54	−4.04	−6.91	1.74
August 80	9.06	9.24	0.53	8.97	9.05	0.55	13.2	13.05	2.15	5.45	5.42	0.17	8.30	8.30	0.28	1.02*	1.41	0.20	−3.91**	−2.53	0.54	−6.91	−6.91	1.74
September 80	9.59	9.51	0.53	8.95	9.25	0.56	12.6	13.09	2.15	5.43	5.40	0.17	8.15	7.97	0.28	1.36	1.47	0.20	−3.51	−2.40	0.54	−4.38*	−6.91	1.74
October 80	9.87	9.47	0.53	9.58	9.56	0.56	10.3*	12.75	2.15	5.47	5.53	0.17	8.15	7.99	0.28	1.45	1.49	0.20	−2.76	−2.44	0.54	−5.99	−6.91	1.74
November 80	9.46	9.62	0.53	9.68	9.72	0.56	9.2	8.82	2.15	5.45	5.48	0.17	8.10	7.96	0.28	1.45	1.48	0.20	−2.99	−2.46	0.54	−4.71	−6.22	1.74
December 80	9.94	9.55	0.53	9.74	9.24	0.56	6.7	6.81	2.15	5.54*	5.29	0.17	8.10	7.94	0.28	1.47	1.54	0.20	−2.00	−2.32	0.54	−5.81	−6.91	1.74
January 81	10.01	9.90	0.53	9.74	9.35	0.56	5.5	4.07	2.15	5.53	5.56	0.17	8.20	7.96	0.29	1.48	1.56	0.20	−2.21	−2.31	0.54	−4.96	−6.60	1.74
February 81	9.71	9.49	0.54	9.74*	9.16	0.56	3.8	2.74	2.16	5.55	5.60	0.17	8.20	7.93	0.30	1.44	1.61	0.20	−2.99*	−2.35	0.55	−6.50	−6.71	1.75
March 81	8.29*	8.83	0.55	8.82	8.80	0.56	3.7	3.56	2.16	5.58	5.65	0.18	8.05	7.98	0.30	1.54	1.62	0.20	−2.66	−2.15	0.55	−6.21	−6.91	1.75
April 81	7.95	8.37	0.55	7.98	8.51	0.56	4.3	3.90	2.16	5.67	5.68	0.18	8.20	8.05	0.30	1.61	1.68	0.20	−2.16	−2.28	0.55	−6.21	−6.91	1.75
May 81	8.12	8.36	0.55	8.05	8.55	0.56	6.5	6.65	2.16	5.64	5.68	0.18	8.20	8.13	0.30	1.68	1.53	0.20	−1.77*	−2.80	0.55	−6.91	−6.91	1.75
June 81	9.90*	9.15	0.55	9.55	8.79*	0.56	8.9	10.02	2.16	5.49	5.57	0.18	8.10	8.34	0.30	1.58	1.61	0.20	−2.08*	−2.64	0.55	−6.91	−6.91	1.75
July 81	10.43**	9.18	0.55	10.22	9.06**	0.56	12.0	12.61	2.16	5.43	5.46	0.18	8.10	8.21	0.30	1.66	1.50	0.20	−2.30	−2.42	0.55	−6.91	−6.91	1.75
August 81	9.85*	9.24	0.55	9.53	9.05	0.56	13.8	13.05	2.16	5.40	5.41	0.18	8.10	8.30	0.30	1.70*	1.41	0.20	−2.99	−2.53	0.55	−5.81	−6.91	1.75
September 81	9.38	9.51	0.55	9.13	9.25	0.56	12.8	13.09	2.16	5.38	5.39	0.18	7.96	7.97	0.30	1.83*	1.46	0.20	−2.87	−2.40	0.55	−6.91	−6.91	1.75
October 81	9.37	9.47	0.55	9.46	9.56	0.56	11.2*	8.82	2.16	5.39	5.46	0.18	8.10	7.99	0.30	1.50	1.49	0.20	−2.25	−2.44	0.55	−5.99	−6.91	1.75
November 81	9.91	9.62	0.55	9.53	9.72	0.56	8.9	8.82	2.16	5.46	5.47	0.18	8.05	7.96	0.30	1.60	1.48	0.20	−2.77	−2.46	0.55	−6.61	−6.58	1.75
December 81	9.97	9.55	0.55	9.86*	9.24	0.56	6.8	6.81	2.16	5.47	5.52	0.18	7.90	7.94	0.30	1.46	1.54	0.20	−2.41	−2.32	0.55	−5.30	−6.91	1.75
January 82	9.88	9.90	0.55	9.85	9.35	0.56	4.7	4.07	2.16	5.52	5.55	0.18	8.00	7.96	0.30	1.56	1.56	0.20	−2.25	−2.31	0.55	−6.91	−6.91	1.75